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Abstract

This paper presents a theoretical model of remanufacturing where a duopoly of original manufacturers produces a component of a final good. The specific component that needs to be replaced during the lifetime of the final good creates a secondary market where independent remanufacturers enter the competition. An environmental regulation imposing a minimum level of remanufacturability is also introduced. The main results establish that, while collusion of the firms on the level of remanufacturability increases both profit and consumer surplus, a social planner could use collusion as a substitute for an environmental regulation. However, if an environmental regulation is to be implemented, collusion should be repressed since competition supports the public intervention better. Under certain circumstances, the environmental regulation can increase both profit and consumer surplus. Part of this result supports the Porter Hypothesis, which stipulates that industries respecting environmental regulations can see their profits increase.

Keywords: remanufacturing, competition, environmental regulation, Porter Hypothesis.

Ce papier présente un model théorique de remanufacturing où un duopole de manufacturiers originaux produit un composant d'un bien final. Ce composant devant être changé, un marché secondaire est créé. Une réglementation environnementale déterminant un niveau minimal de remanufacturabilité est introduite au modèle. Les principaux résultats indiquent d'une part que la collusion des firmes sur le niveau de remanufacturability augmente les profits et le surplus du consommateur et d'autre part qu'un planificateur social pourrait substituer la réglementation environnementale par la collusion. Cependant, lorsqu'une réglementation environnementale est prévue, la collusion devrait être réprimée puisque la compétition s'accorde mieux avec une intervention publique. Sous certaines conditions, la réglementation peut aussi augmenter les profits et le surplus du consommateur. Une partie de ces résultats coïncide avec l'hypothèse de Porter stipulant que les industries soumises à des réglementations environnementales peuvent voir une augmentation de leurs profits.

Mots clés: remanufacturing, compétition, réglementation environnementale, hypothèse de Porter.

JEL classification: H23, L10, L51, Q53, Q58

1 Introduction

Remanufacturing is a specific type of recycling in which used durable goods are repaired to a like-new condition. Both remanufacturing and recycling avoid post-consumption waste while reducing the use of raw materials. However, recycling is an energy-intensive process that conserves only material value. In attempting to meet multiple environmental objectives, remanufacturing can be a more suitable option; it preserves most of the added-value by giving a second life to the product and, typically, reduces the use of energy by eliminating production steps. This paper develops a model of remanufacturing where a government may either favor an environmental collusion between producers or introduce an environmental regulation setting a minimum level of remanufacturability. The impact on profits and consumer surplus is analyzed.

The level of remanufacturability defines the technical attributes that facilitate the product reuse and refurbishing at the end of its life. In this sector, waste reuse becomes a design objective, so that remanufacturability can be seen as a form of green design. Moreover, since it deals with end-of-life product management and recycled materials, remanufacturing belongs to the eco-industry as defined by the OECD and Eurostat.[1]

After a product's first life, recycled material can be redirected towards any industry. On the contrary, the material going through the remanufacturing process goes back to the same industry. Then, remanufacturing-oriented designs permit the *original manufacturers* (OMs) to access the secondary market's benefits. Indeed, while remanufactured products are sold at 60 to 70 percent of the new products' price, their production accounts for only 35 to 60 percent of the original costs [Giuntini and Gaudette 2003]. Therefore, when new products can

[1] Eco-industries "[...] include cleaner technologies, products and services which reduce environmental risk and minimize pollution and resource use." ["The Environmental Goods and Services Industry: Manual for Data Collection and Analysis" OECD, 1999]

For an introduction to the literature on green design see Fullerton and Wu (1998), Eichner and Pethig (2001) and Eichner and Runkel (2005). For the literature on eco-industry, see David and Sinclair-Desgagné (2005) and Canton (2008).

be substituted with remanufactured ones, original manufacturers may undertake profitable remanufacturing initiatives. Xerox, Kodak, Ford Motor Company and Mercedes-Benz are examples of corporations that could reduce their production costs with voluntary product recovery [Toffel 2004]. These corporations are part today of a 60-100 billion dollar industry according to the sources.

In this framework, the car parts industry is of particular interest. Combined, alternators and starters represent 80 percent of remanufactured products [Kim *et al.* 2008]. Valeo and Bosch are two important alternator producers in Europe. They started remanufacturing activities in the early 90's, following the announcement of legislation prohibiting the production, sale and use of asbestos[2]: a technological constraint that has made alternator remanufacturing commercially viable. Remanufactured alternators and starters are produced at a fraction of the original cost. Steinhilper (1998) shows that on average they require 14% of the energy and 12% of the material necessary for the production of new ones. Representative of the remanufacturing industry, this reduction in energy and raw material consumption makes remanufacturing both environmentally desirable and industrially profitable. Inspired by the alternator anecdote, one of the main purposes of this paper is to describe how green designs can be costly for the industry and become profitable once an environmental regulation is introduced.

Over the years, profitability concerns have made remanufacturing a hot topic in the engineering and managerial worlds, witness the flourishing literature on reverse logistic, stock planning, material demand and return, and case studies.[3] Nonetheless, there are only a handful of economic studies that consider the effect of public interventions on remanufacturing activities [Webster and Mitra 2007; Mitra and Webster 2008].

The current paper proposes a theoretical model of remanufacturing framed on the partic-

[2]This legislation was enacted in 1993 in Germany and in 1997 in France, the respective headquarters of Bosch and Valeo, with the European Union following suit in 1999 [European Commission 1999].

[3]See for instance Ferrer (1997), Kiesmuller and Laan (2001), Majumder and Groenevelt (2001), Lebreton and Tuma (2006), Ferrer and Swaminathan (2006), Chung and We (2008).

ularities of the alternator industry. A duopoly of OMs compete on the primary market where they face the threat of an outsider; they also compete on the aftermarket where consumers of remanufactured products may alternatively use the services of competitive *independent remanufacturers* (IRs). The model pins down the different incentives in the technology selection determining the level of remanufacturability and explores the consequences of environmental regulations. Particularly, it explains why original alternator manufacturers refrained from adopting a voluntary withdrawal of asbestos from their production in order to launch profitable remanufacturing activities.

Most previous research works have assumed a fixed level of remanufacturability. A study by Debo *et al.* (2005) analyzes the technology selection for remanufacturable goods when a higher level of remanufacturability may invite entry by IRs.[4] Stronger competition on the remanufacturing market pulls down prices and OMs show lower interest in costly production technology. Therefore, governmental interventions promoting competition on the aftermarket have an adverse effect on the level of remanufacturability. This corroborates the observation of Ferrer (2000) who states that remanufacturing is viable only if the remanufactured product is priced above its marginal cost. Following Debo *et al.* (2005), the current model considers the positive one-way externality of remanufacturability on IRs. However, OMs can endogeneously choose among a range of existing technologies and reduce, for low levels of remanufacturability, the impact of technological spillovers. Also, studies that observe effects of competition on the remanufacturing market generally assume away competition on the primary market; *i.e.* they assume a monopolistic original manufacturer.[5] The current model innovates by considering a duopoly and the threat of an outsider. One

[4]Since remanufacturability gives the products a positive value at the end of their life, OMs have the incentive to offer remanufacturable products when the end of life value is reflected in the original product price.

[5]See for instance Carlton and Waldman (2009), Mitra and Webster (2008), Debo *et al.* (2005) and Majumder and Groenevelt (2001). In a different context, Heese *et al.* (2005) study a duopoly that compete on the primary market. In their model, new products have a positive initial remanufacturability level. Hence the first mover in launching take-back strategy can deter the competitor by offering a new product with a lower price that includes a discount for the consumer who will return the used product.

major point that distinguishes the current model from the previous literature is the perfect market segmentation between new and remanufactured products. In an industry where there is a need for compatibility between the component and the final good, and where the component can be remanufactured several times, the need for new good production on the aftermarket is negligible. In the alternator industry, more than 90% of the aftermarket is filled with remanufactured products.

Other literatures that can be used to understand this remanufacturing market include the literature on durable goods with repeated purchases as well as the economics of innovation in the presence of technological spillovers. These topics will be discussed below.

Finally, similarities between recycling and remanufacturing are such that they use comparable public interventions. Webster and Mitra (2007) and Mitra and Webster (2008) have pointed out that take-back regulations as well as subsidies can encourage remanufacturing activities. These tools have also been studied in the recycling literature [Fullerton and Wu 1998; Eichner and Pethig 2001; Eichner and Runkel 2005; Toffel *et al.* 2008]. Furthermore, because recyclable and remanufacturable products present common characteristics in their conception [Steinhilper 1998], regulations aimed at either recycling or remanufacturing may interchangeably foster one activity or the other.

The main results show that in the absence of environmental regulation, collusion leads to a higher level of remanufacturability while increasing both profits and consumer surplus. When remanufacturability is environmentally desirable, the government may use collusion on the level of remanufacturability as a substitute for an environmental regulation. In the absence of public intervention, the threat of entry on the primary market sticks the original price at the production cost of non-remanufacturable products. Consequently, the OM who decides to produce remanufacturable goods must absorb the full cost of remanufacturing-oriented technologies. This phenomenon explains what has refrained alternator producers to adopt remanufacturable technologies prior to the regulation on asbestos. The introduction of an environmental regulation imposing a minimum level of remanufacturability reduces the threat of the outsider, since potential entrants will be subjected to the same regulation. Softened market competition leads to an increase in the original product price and correspondingly higher OMs profits. This result is in line with the Porter Hypothesis stating that environmental regulations may increase profits in regulated industries. Finally, under specific circumstances, an environmental regulation can also increase consumer surplus.

The model is introduced in the next section, which sets technologies, demands and the industrial structure. Section 3 completes the assumption on technology and describes the optimization problem for two cases: non-cooperation and collusion. Section 4 observes the effect of an environmental regulation. Section 5 concludes.

2 The Model

A duopoly of identical original manufacturers (OMs) produce an intermediate good m (the alternator), which enters as a component of a final consumption good (the vehicle). This constitutes the primary market and the component's first life. Since the same car goes through two or three alternators [Kim *et al.* 2008], the lifetimes of the alternator and the vehicle are respectively l and L, with $l < L$. Consequently, consumers of the final good all have to replace the defective component at each of the b replacement periods, where $b = (L/l) - 1$. This creates an aftermarket.

The alternator's original life aims specifically at the new vehicle industry with one alternator per vehicle. Used alternators can be remanufactured several times and, at any moment, there are an equal number of cars and alternators on the market.

When they originally produce a remanufacturable component, OMs participate in the aftermarket by recovering and remanufacturing used products. On this market, however, they face competition from independent remanufacturers (IRs). In 2005, IRs represented 54% of the aftermarket for automotive parts in Europe and 66% worldwide.[6]

[6] Source: Fernand J. Weiland: "Remanufacturing Automotive Mechatronics and Electronics" available at

2.1 Technology

Each OM i, $i \in \{1,2\}$, controls its level of remanufacturability q_i, a technology choice corresponding to the ease with which a used product can be remanufactured[7] and leading to decreasing unit remanufacturing costs $c_r(q_i)$ and $c_s(q_i)$, for OMs and IRs respectively. However, OMs benefit from economies of scope between new and remanufactured products[8] and, for any given q, have lower unit remanufacturing costs than IRs. This *technological advantage* for OMs over the IRs is represented by the following properties:

$$c_s(q) - c_r(q) \geq 0; \quad \text{and asymptotically:} \quad \lim_{q_i \to \infty} (c_s(q) - c_r(q)) = 0. \tag{1}$$

For large levels of remanufacturability, remanufacturing becomes equally accessible for IRs.

To make the original product more remanufacturable, OMs bear additional production costs reflected by an increasing and convex initial manufacturing cost, $c_m(q_i)$.

2.2 Demand functions

The demand for the component is segmented into two types: the demands for new and for remanufactured products.

The demand for new products m is driven by final good producers. It is assumed that any variation in the original component price represents a small share of the final good production cost and, hence, the demand for m stays inelastic for a reasonably large range of

http://www.apra-europe.org.

[7] In most models [see for instance Debo *et al.* 2005; Majumder and Groenevelt 2001; Ferrer and Swaminathan 2006] the level of remanufacturability is the percentage of remanufacturable used products. While the share of un-remanufacturable cores can exceed 30% for certain products, it is less than 15% for alternators [Kim *et al.* 2008]. In the present model, this number is assumed to be negligible so that the alternator/vehicle ratio stays equal to 1.

[8] Carlton and Waldman (2009) also assume economies of scope between the production of new parts and remanufactured ones.

prices (or until a certain choke price). Except for great demand elasticities, this assumption does not affect the results, but lightens the model. For simplicity, m is normalized to 1.

The demand for remanufactured products comes from final consumers. Since the price of alternators remanufactured by OMs is between 50 to 60% of the price of new alternators [Kim *et al.* 2008], it is assumed that consumers always opt for remanufactured products.[9] Indeed, remanufactured starters and alternators cover more than 90% of the replacement market [Steinhilper, 1998]. Consumer types are uniformly distributed over $\theta \in [0, 1]$, where $\theta + \alpha$ is the willingness to pay for a replacement good. The positive constant α indicates that even individuals from the lower bound are willing to pay a positive amount. When remanufacturing used products, OMs provide the properties and warranty of new goods while IRs supply products of lower quality.[10] As a result, consumers will express lower willingness to pay for IRs' products. The parameter $\delta \in [0, 1]$ reflects this perceived depreciation in quality.

At each replacement period, individuals maximize their consumer surplus by purchasing a product coming from an OM, an IR or no product at all. This maximization problem is given by: $\max[\theta + \alpha - p_r, (1 - \delta)\theta + \alpha - p_s, 0]$, where p_r and p_s are respectively the selling price of OMs and IRs' products. Because the component price represents a small fraction of the final good's value, $\alpha \geq p_s$ mimics the inelastic aftermarket and ensures that everyone consumes a replacement good; that is, $r + s = 1$, where variables r and s designate the demand for components remanufactured by the OMs and the IRs respectively. Figure 1 illustrates the willingness to pay for the two differentiated products.

[9] In other models, two scenarios generally bring new products on the aftermarket. In the first one, products differentiation leads to a positive demand for new replacement products (for instance, in the case of rapid obsolescence like in the computer market). In the second one, the elastic aftermarket demand cannot be fulfilled solely with remanufactured products (like in the disposable camera market). In the alternator industry, the need for compatibility makes product differentiation negligible between new and remanufactured products. Also, the potential supply of remanufactured products correspond to the potential demand since there is one alternator per vehicle and each alternator can be remanufactured several times.

[10] For the same two year warranty, OMs' remanufactured products are twice the price of IRs' products [Kim *et al.* 2008]. This suggests a difference in quality. For instance, IRs' products may require more visits to the mechanic.

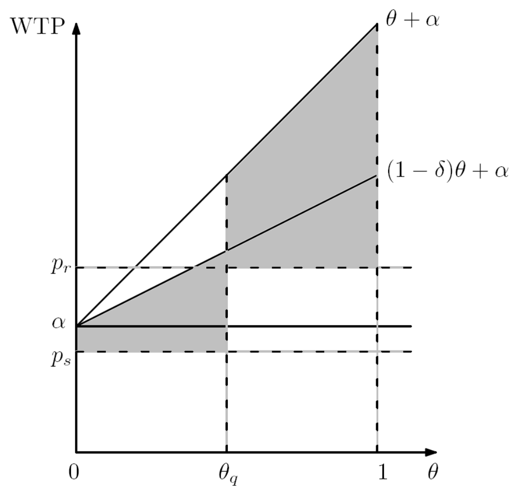


Figure 1: Willingness to pay and consumer surplus

The set of consumers buying remanufactured products from the OMs is defined by θ such that $\theta + \alpha - p_r \geq (1-\delta)\theta + \alpha - p_s$, or equivalently: $\theta \geq (p_r - p_s)/\delta$. In Figure 1, given prices p_r and p_s, individual θ_q is indifferent between the two products. Types $\theta \in [\theta_q, 1]$ prefer OMs' services while the others, $\theta \in [0, \theta_q]$, purchase lower quality goods. The shaded area corresponds to the total consumer surplus at each replacement period.

Given a uniform distribution for θ, the demand for products remanufactured by the OMs at each period is $r = 1 - (\frac{p_r - p_s}{\delta})$ so that the inverse demand function is:

$$p_r = \delta(1-r) + p_s. \tag{2}$$

For any positive value of the parameter δ, this depicts the observed price difference between alternators remanufactured by the OMs and the IRs. This premium adds an incentive to the OMs that stays unexplored in the literature.

2.3 Industrial structure

Competition in the industry is described by the following four-stage game. In the first stage, two identical OMs produce the original component and control its level of remanufacturability q_i. Two different competitive environments will be considered in determining q_i: non-cooperation and collusion. These scenarios internalize, or not, the fact that firms can free-ride on each other's technology selection q_i.[11]

In the second stage, OMs set the original product's prices and quantities p_{mi} and m_i. They face the threat of an outsider that would seize any profit opportunities originating from the original market but who stays blind on what occurs on the remanufacturing market.[12] This threat forces price competition between OMs, reflecting the automotive industry: original components being perfectly substitutable, vehicle manufacturers can switch from one supplier to the other as soon as a lower price is offered.

The third and fourth stages occur on the aftermarket. Although this market is shared with IRs, OMs hold an oligopolistic power on high quality products. In the third stage, OMs compete by choosing quantities r_i. In the final stage, IRs compete perfectly and their remanufactured good's price is established.

Because of the inelastic aftermarket size, it is assumed that OMs and IRs cannot discriminate between products that have different levels of remanufacturability (everything has to be remanufactured).

OMs have perfect knowledge of each other. Their decisions in each stage are made and applied simultaneously. They also have perfect information about IRs' characteristics. Since

[11] It has been observed in the alternator industry that *i*) Bosch remanufactures Valeo's alternators; *ii*) Valeo remanufactures Bosch's alternators; and *iii*) although, for a given vehicle model, alternators must meet standards set by the automobile constructor, Bosch and Valeo's products are not identical.

[12] Two arguments are proposed in order to explain this behaviour. The first one assumes that reputation is an important factor in being considered as an OM and, therefore, new entrants cannot benefit from a price premium on the aftermarket. The second point considers that incumbents face less risk and are more willing to accept delayed profits.

OMs are identical, a symmetric subgame-perfect equilibrium in pure strategies in the four-stage game is computed.

3 The optimization problem

Under the market clearing conditions, $m_1+m_2=1$ and $r_1+r_2=r$. The OMs' profit function depends on both their activities on the primary market and the remanufacturing market:

$$\pi_i = (p_{mi} - c_m(q_i))m_i + \underbrace{\sum_{t=1}^{b} \beta_l^t [(p_r - m_i c_r(q_i) - m_j c_r(q_j))r_i]}_{R_i(r_i, r_j, m_i, m_j, q_i, q_j)} \text{ for } i = 1, 2 \text{ and } j \neq i$$

where $p_r = \delta(1-r) + p_s$ from equation (2) and $0 < \beta_l < 1$ is the discount factor associated with the length of time l. The first term is the net profit from the original market while $R_i(r_i, r_j, m_i, m_j, q_i, q_j)$ corresponds to the discounted profit from all the remanufacturing periods. Because used products randomly go to any remanufacturer, the remanufacturing cost depends on the technology selection of each OM and is weighed by their respective participation in the original market.

3.1 Prices and quantities

Using backward induction, the final stage is solved first. IRs are perfectly competitive and the selling price p_s is set at the average unit cost of remanufacturing:

$$p_s = m_i c_s(q_i) + m_j c_s(q_j). \tag{3}$$

In the third stage, each OM i maximizes its profit on the aftermarket by choosing its supply of remanufactured products r_i, and by taking the supply choice of its opponents r_j as well as the levels of remanufacturability (q_i, q_j) as given. It also considers IRs' behavior through equation (3). The OMs maximization problem at this stage is:

$$\begin{aligned}\max_{r_i \geq 0} R_i &= \sum_{t=1}^{b} \beta_l^t[(\delta(1-(r_i+r_j)) + m_i(c_s(q_i) - c_r(q_i)) + m_j(c_s(q_j) - c_r(q_j)))r_i] \\ &\quad \text{for } i = 1,2 \text{ and } j \neq i\end{aligned}$$

and the first-order condition is:

$$\frac{\partial R_i}{\partial r_i} = 0 \Longleftrightarrow \sum_{t=1}^{b} \beta_l^t[\delta - \delta r_j - 2\delta r_i + m_i(c_s(q_i) - c_r(q_i)) + m_j(c_s(q_j) - c_r(q_j))] = 0. \quad (4)$$

The Nash equilibrium for the supply of remanufactured products is defined by:

$$r_i^*(m_i, m_j, q_i, q_j) = \frac{\delta + m_i(c_s(q_i) - c_r(q_i)) + m_j(c_s(q_j) - c_r(q_j))}{3\delta} \text{ for } i = 1,2 \text{ and } j \neq i \quad (5)$$

and the second-order condition for an interior maximum is respected when evaluated at the equilibrium r_i^*.

Here, IRs play a passive role since their price is driven by the OMs' choice of remanufacturability (equation 3). Also, they only have a residual participation in the aftermarket; the demand for their products depends on OMs' supply decisions with $s^* = 1 - 2r_i^*$. Note that the choice of $2r_i^*$ also corresponds to OMs' aftermarket share.

In the second stage, the two OMs compete on the primary market where the threat of the outsider keeps the component price p_{mi} at the minimum production cost; that is,

$$p_{m1} = p_{m2} = c_m(0). \quad (6)$$

By offering a common original price, OMs share this market equally with $m_i = 1/2$. If a higher price is set, the outsider, by proposing the lowest level of remanufacturability, can make a strictly positive profit and deter competitors. Note that in spite of that restriction, OMs may still optimally choose a positive level of remanufacturability and, consequently, run a deficit on the primary market ($p_{mi} - c_m(q_i) = c_m(0) - c_m(q_i) \leq 0$). This is consistent with the existing literature on durable goods with switching costs. In the current model of repeated purchases, the need for compatibility between the component and the final good induces a consumer cost of switching to other models of alternators. One standard result shows how switching costs cause a price war for initial market share.[13] Here, fixing the original price at the lowest production cost prevents the entry by the outsider and secures the original market to the duopoly.

Two situations are considered for the determination of q_i and q_j in the first stage. The first case reflects the non-cooperative problem that occurs when an OM remanufactures used products from random origin and free-ride on the technology selection of the other. The second case considers the possibility of an agreement between the OMs. These situations are explicitly formulated in subsections 3.3 and 3.4.

Before solving for the choice of remanufacturability, an important assumption on the technology selection is introduced in the coming subsection.

3.2 Assumption on the technology selection

At this step, only the first stage equilibrium remains to be solved and everything thereafter depends on the technology selection (q_i, q_j) taken as given. The profit function is:

$$\pi_i^* = (c_m(0) - c_m(q_i))\frac{1}{2} + \underbrace{\sum_{t=1}^{b} \beta_l^t [\delta r_i^*(q_i, q_j)^2]}_{R_i(q_i, q_j)} \tag{7}$$

[13] See Klemperer (1995) for an introduction to the literature. The author relates the example of banks, giving free banking services to college students. Students who open current accounts are then charged high fees once they graduate. Expected profits in subsequent periods induce a price war for initial market share.

where the optimal supply of remanufactured products (equation 5) is reduced to:

$$r_i^*(q_i, q_j) = \frac{\delta + c_s(q_i) - c_r(q_i)}{6\delta} + \frac{\delta + c_s(q_j) - c_r(q_j)}{6\delta} \tag{8}$$

when the individual market share in equilibrium, $m_i = 1/2$, is taken into account.

A variation in q affects the profit through two channels: i) the original production cost $c_m(q_i)$; and ii) the total net revenue of remanufacturing activities $R_i(q_i, q_j)$. Since OMs are identical, the analysis will focus on symmetric equilibria $q_i = q_j = q$. OMs know that, for any given q, their profit depends substantially on their technological advantage: $c_s(q) - c_r(q)$. The comparative static

$$\frac{\partial r_i^*}{\partial q} = \frac{c_s'(q) - c_r'(q)}{3\delta} \tag{9}$$

indicates that, with an increasing technological advantage, a higher level of remanufacturability leads to a larger aftermarket share and, consequently, higher remanufacturing revenues.

The following assumption completes the description of the technological advantage introduced in section 2.1. It is assumed that OMs have access to a wide range of remanufacturable and substitutable technologies. In dealing with the fact that IRs benefit from the positive externality of remanufacturability (through $c_s'(q) < 0$), OMs endogeneously rank order technologies with respect to their marginal technological advantage, $c_s'(q) - c_r'(q)$. In other words, OMs will prioritize technologies where their relative cost reduction is the largest. Consequently, for low levels of remanufacturability, $c_s'(q) - c_r'(q)$ is positive and large. This is because the wide technology choice allows OMs to shape the original product in order to suit their own remanufacturing facilities or assembly lines.[14] As the level of remanufactura-

[14] For instance, in the toner cartridge industry, some firms have added an electronic key in their remanufacturable cartridges that must be reset by the OM. This leads to an increase in the relative remanufacturing cost of IRs [Majumder and Groenevelt 2001].

bility goes higher, the range of technology choices lessens and $c_s'(q)-c_r'(q)$ decreases. As long as $c_s'(q)-c_r'(q)>0$, OMs have an incentive to choose higher levels of remanufacturability since it increases their aftermarket share (see equation 9). At some $q=\widehat{q}$, higher levels of remanufacturability leads to the adoption of technologies that reduce their aftermarket share with $c_s'(q)-c_r'(q)\leq 0$. This situation occurs for instance when a larger q eliminates disassembly or reassembly steps originally costlier for IRs.[15] For high levels of remanufacturability, $q>\widetilde{q}$, OMs are constrained with end of tail technologies, *i.e.* non-substitutable technologies specifically designed for high performance. Beyond $\widetilde{q}$, higher levels of remanufacturability slowly reduce the gap between OMs' and IRs' remanufacturing costs. Formally, with $\widehat{q}<\widetilde{q}$, the technological advantage is described by equation (1) and:

$$c_s'(q)-c_r'(q)\begin{cases}>0 \text{ for } q<\widehat{q}\\ =0 \text{ for } q=\widehat{q}\\ \leq 0 \text{ for } q>\widehat{q}\end{cases} \quad \text{and} \quad c_s''(q)-c_r''(q)\begin{cases}<0 \text{ for } q<\widetilde{q}\\ =0 \text{ for } q=\widetilde{q}\\ \geq 0 \text{ for } q>\widetilde{q}\end{cases} \tag{10}$$

This assumption is in line with a broader literature on innovation. The first part, when $c_s'(q)-c_r'(q)>0$, shows the predominance of post-innovation competitive advantage while the second part, when $c_s'(q)-c_r'(q)\leq 0$, is the result of an increasing relative rate of technological spillovers.[16] The presence of IRs therefore determines, through technology, the extent to which OMs reach the aftermarket. Variation of the technological advantage with the level of remanufacturability is illustrated in Figure 2.

[15] By the mean value theorem, $c_s'(q)-c_r'(q)\leq 0$, for at least some q, is an essential condition for the respect of equation (1).

[16] See for instance d'Aspremont and Jacquemin (1988) or Celleni and Lambertini (2009). Goel (1990) studies the R&D decision of a Stackelberg leader (the OMs here) when the follower (the IRs here) benefits from one-way spillovers. The author argues that the leader sustains a dominant role when R&D investment implies a greater cost reduction than for the follower. In the current model, that is $c_s'(q)-c_r'(q)>0$.

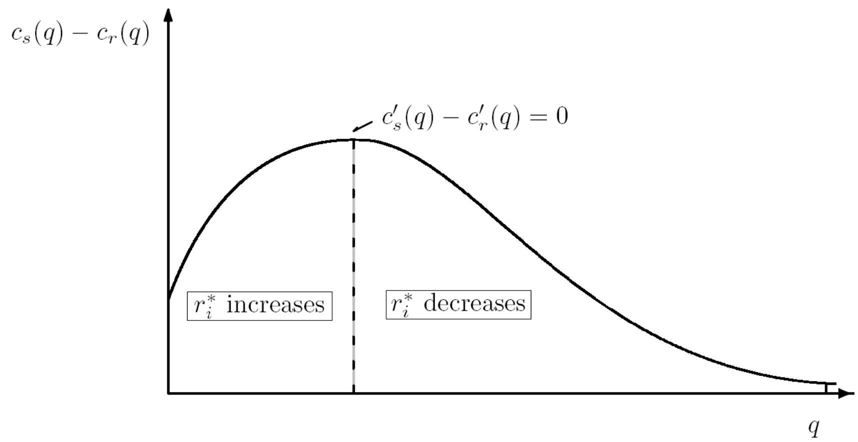


Figure 2: Technological advantage

3.3 The non-cooperative case

Each manufacturer i maximizes its profits by choosing the level of remanufacturability q_i, taking the technology choice of the other q_j as given and considering the optimal supply of remanufactured products $r_i^*(q_i, q_j)$. Used products are randomly dispatched among remanufacturers (both OMs and IRs) and, therefore, the technology selection of i is subject to free-riding. The maximization problem is:

$$\max_{q_i \geq 0} \pi_i^* = (c_m(0) - c_m(q_i))\frac{1}{2} + \sum_{t=1}^{b} \beta_l^t \left[\delta r_i^*(q_i, q_j)^2\right] \text{ for } i = 1, 2 \text{ and } j \neq i$$
$$\text{s.t. } r_i^*(q_i, q_j) = \frac{\delta + c_s(q_i) - c_r(q_i)}{6\delta} + \frac{(\delta + c_s(q_j) - c_r(q_j))}{6\delta},$$

and the first-order condition is:

$$\frac{\partial \pi_i^*}{\partial q_i} = 0 \Longleftrightarrow -\frac{c'_m(q_i)}{2} + \sum_{t=1}^{b} \beta_l^t \left[\frac{2\delta(c'_s(q_i) - c'_r(q_i))}{6\delta} r_i^*(q_i, q_j)\right] = 0$$
$$\text{for } i = 1, 2 \text{ and } j \neq i$$

where the marginal cost of a higher level of remanufacturability is equal to the marginal revenue generated when the choice of the other is taken as fixed. The symmetric Nash equilibrium q^*_{nc} is defined by:

$$-c'_m(q^*_{nc}) + \underbrace{\sum_{t=1}^{b} \beta_l^t \left[\frac{2(c'_s(q^*_{nc}) - c'_r(q^*_{nc}))}{3} r^*_i(q^*_{nc}) \right]}_{R'(q^*_{nc})} = 0 \tag{11}$$

where the subscript nc stands for the non-cooperative case. It is assumed that the second-order condition for an interior maximum is respected when evaluated at the symmetric equilibrium q^*_{nc}.[17] In the presence of a corner solution $q^*_{nc} = 0$, the component is not remanufacturable.

A positive q^*_{nc} denotes *voluntary* remanufacturing activities in the industry.

3.4 The collusive case

In this scenario, OMs agree on a unique level of remanufacturability $q_i = q_j = q_c$, where the subscript c refers to the collusive case. OMs internalize each other's free-riding behaviour by choosing the level of remanufacturability q^*_c that maximizes joint profit (however they still suffer from IRs' free-riding activities), which becomes:

$$\max_{q \geq 0} \pi^*_1 + \pi^*_2 = (c_m(0) - c_m(q_c)) + 2 \sum_{t=1}^{b} \beta_l^t [\delta r^*_i(q_c)^2] \tag{12}$$

$$\text{s.t. } r^*_i(q_c) = \frac{\delta + c_s(q_c) - c_r(q_c)}{3\delta}.$$

[17] The second-order condition is $-c''_m(q^*_{nc}) + R''(q^*_{nc}) \leq 0$. For any given q, $R''(q) = \sum_{t=1}^{b} \beta_l^t \left[\frac{2}{3} \left(\frac{(c''_s(q) - c''_r(q))}{3} r^*_i(q) + \frac{(c'_s(q) - c'_r(q))^2}{3\delta} \right) \right]$. From the specifications of equation (10), the condition is satisfied in a large neighbourhood of $q = \widehat{q}$. Note that if $c''_s(q) - c''_r(q)$ is monotonically increasing for $q < \widetilde{q}$, then when a maximum exists, it is included in the neighbourhood of $q = \widehat{q}$ and it is unique.

The first-order conditions is:

$$\frac{\partial \pi_i^*}{\partial q} = 0 \Longleftrightarrow -\frac{c_m'(q_c^*)}{2} + \underbrace{\sum_{t=1}^{b} \beta_l^t \left[\frac{2(c_s'(q_c^*) - c_r'(q_c^*))}{3} r_i^*(q_c^*)\right]}_{R'(q_c^*)} = 0 \tag{13}$$

and it is assumed that the second-order condition for an interior maximum is respected when evaluated at q_c^*.[18]

3.5 Welfare analysis

The consumer surplus is now compared for the two scenarios. Here, consumer surplus on the original market is ignored since prices and quantities stay unchanged. Referring to Figure 1, the consumer surplus on the aftermarket is defined by: $S_r = \sum_{t=1}^{b} \beta_l^t \left[\int_{\theta_q}^{1} (\theta + \alpha - p_r)\partial\theta + \int_0^{\theta_q} ((1-\delta)\theta + \alpha - p_s)\partial\theta\right]$. Markets clear in equilibrium, therefore $1 - \theta_q = 2r_i^*$. Using (2), (3) and (8), the total consumer surplus for a given q becomes:

$$S_r(q) = \sum_{t=1}^{b} \frac{\beta_l^t}{2} \left[(1-\delta) + \delta r_i^*(q)^2 + 2(\alpha - c_s(q))\right]. \tag{14}$$

Proposition 1 *Collusion, compared to non-cooperation, leads to:*

i) *a higher level of remanufacturability:* $q_{nc}^* < q_c^*$*;*

ii) *a larger market share of good quality remanufactured products:* $r_i^*(q_{nc}^*) < r_i^*(q_c^*)$*;*

iii) *higher profits:* $\pi_i^*(q_{nc}^*) < \pi_i^*(q_c^*)$*; and*

iv) *higher consumer surplus:* $S_r(q_{nc}^*) < S_r(q_c^*)$*.*

Proof: The optimal choice of q_{nc}^* and q_c^* are determined by equations (11) and (13). From the second-order condition, $-c_m''(q)/2 + R''(q) \leq 0$. Therefore, $q_{nc}^* < q_c^*$. Both q_{nc}^* and

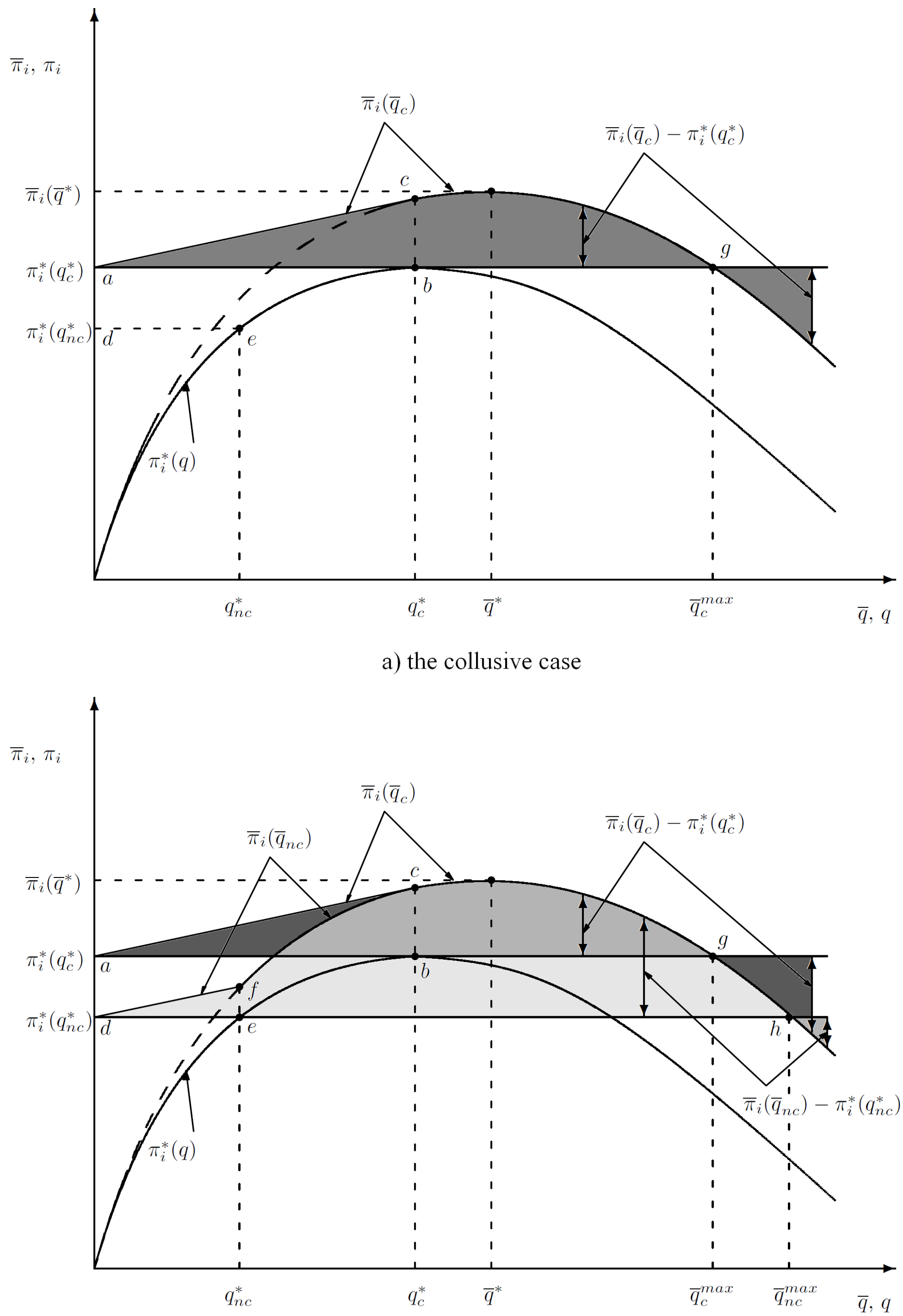
[18] The second-order condition is $-c_m''(q_c^*)/2 + R''(q_c^*) \leq 0$. See footnote 17 for details.

q_c^* are in a neighbourhood where $R'(q) > 0 \iff (c'_s(q) - c'_r(q)) > 0$. Hence, from equation (9), $r_i^*(q_{nc}^*) < r_i^*(q_c^*)$. $\pi_i^*(q_{nc}^*) < \pi_i^*(q_c^*)$ because the externality is internalized. We can find that $\partial S_r(q)/\partial q = \sum_{t=1}^{b} \frac{\beta_l^t}{2}[\delta 2r_i^*(q)\partial r_i^*(q)/\partial q - 2c'_s(q)]$. Since $R'(q) > 0 \iff \partial r_i^*(q)/\partial q > 0$, we have that $\partial S_r(q)/\partial q \mid_{q=q_{nc}^*,\ q_c^*} > 0$ and $S_r(q_{nc}^*) < S_r(q_c^*)$.

Figure 3 a) illustrates $\pi_i^*(q)$ (the lower curve) and shows $q_{nc}^* < q_c^*$ as well as $\pi_i^*(q_{nc}^*) < \pi_i^*(q_c^*)$ (points e and b). When the economy changes from non-cooperation to collusion, prices in the remanufacturing sector (equations 2 and 3) strictly decrease while the market share of good quality products increases. Therefore, collusion benefits not only producers but also consumers. This result recalls Carlton and Waldman (2009) where the monopolist on the original market is also the low-cost remanufacturer. Comparing with the competitive case, monopolizing the remanufacturing market increases welfare since used products are remanufactured in the lowest cost manner. In their model however, the monopolist captures all the benefits and the consumer surplus stays unchanged.

Proposition 1 suggests that a government could substitute environmental regulations by legislating industrial agreements on the level of remanufacturability. The parallel can be made with the National Cooperative Research Act of 1984, in the US, which promotes collusion on innovation and R&D. Extended producer responsibility, a new type of regulation where producers are responsible for their end-of-life product management,[19] also offers platforms where certain kinds of collusions are encouraged. In the alternator industry, these agreements could take place within manufacturers and remanufacturers associations like the international Automotive Parts Remanufacturers Association or the United States Council for Automotive Research.[20]

[19]See for instance the EU Waste Electrical and Electronic Equipment (WEEE) Directive.
[20]See http://apra.org/ and www.uscar.org.



a) the collusive case

b) the collusive and the non-cooperative cases

Figure 3: Profit with and without regulation

4 Environmental regulation

In this economy, the government may decide to introduce an environmental regulation which establishes a minimum level of remanufacturability, denoted by $\overline{q}$.

Here, the objective is not to solve for the social planner's problem, but to observe how the industry would react in case of an environmental regulation. In particular, the analysis shows under which conditions the OMs go along with the regulation or resist compliance with it.

4.1 Public intervention

Under public intervention, the four stages stay the same but firms face a more stringent technological constraint: $q_i \geq \overline{q}$. Because this regulation applies also to the outsider, the minimum production cost increases at $c_m(\overline{q})$ and the second stage equilibrium leads to an increased original component's price:

$$p_{m1} = p_{m2} = c_m(\overline{q}).$$

Hence, the profit function becomes:

$$\overline{\pi}_i(\overline{q}_k) = (c_m(\overline{q}) - c_m(\overline{q}_k))\frac{1}{2} + \sum_{t=1}^{b} \beta_l^t \left[\delta r_i^*(\overline{q}_k)^2\right] \tag{15}$$

where $\overline{\pi}_i$ and $\overline{q}_k$ designate the profit and the optimal level of remanufacturability under environmental regulations. With $k \in \{nc, c\}$, equation (15) stands for either the non-cooperative or the collusive case and respects the equilibrium condition which stays equation (11) or (13).

An environmental regulation will be *effective* if it is larger than voluntary remanufacturability, i.e. when $\overline{q} > q_k^*$. However, if a regulation applies to different industries with uneven remanufacturing initiatives, the regulation might be *non-effective* for some industries with

$\overline{q} < q_k^*$. In this case, the regulation constraint is not biding and the selected level of remanufacturability stays unchanged. The applied level of remanufacturability and the difference in profits before and after regulation are:

$$\overline{q}_k = \begin{cases} q_k^* \text{ if } q_k^* \geq \overline{q} \\ \overline{q} \text{ if } q_k^* \leq \overline{q} \end{cases} \tag{16}$$

$$\overline{\pi}_i(\overline{q}_k) - \pi_i^*(q_k^*) = \begin{cases} \frac{(c_m(\overline{q}) - c_m(0))}{2} \text{ if } q_k^* \geq \overline{q} \\ \frac{(c_m(q_k^*) - c_m(0))}{2} + \sum_{t=1}^{b} \beta_l^t [\delta(r_i^*(\overline{q})^2 - r_i^*(q_k^*)^2)] \text{ if } q_k^* \leq \overline{q} \end{cases} \tag{17}$$

Figure 3 a) shows how profits vary with the imposition of a regulation in the collusive case. Figure 3 b) combines both the collusive and the non-cooperative cases. The vertical distance between the curves $\overline{\pi}_i(\overline{q}_k)$ and the horizontal lines $\pi_i^*(q_k^*)$ describes the difference in profits due to all possible levels of regulation. The light and medium shade areas show the non-cooperative case while the medium and dark shade areas exhibit the collusive case.

When the regulation is non-effective (i.e. when $\overline{q}_k = q_k^* \geq \overline{q}$), the level of remanufacturability stays unchanged. However, the OMs' profit increases by $(c_m(\overline{q}) - c_m(0))/2$ due to the higher original product price. For the collusive (non-cooperative) case, this corresponds to the vertical distance in the triangle abc (def).

An effective regulation ($\overline{q}_k = \overline{q} > q_k^*$) influences OMs' profits through two effects. First, price and cost are now equal on the primary market and OMs' initial deficit vanishes. This shifts up profits by $(c_m(q_k^*) - c_m(0))/2$. For the collusive (non-cooperative) case, this is the vertical distance bc (ef). Second, a higher level of remanufacturability influences OMs' technological advantage and, consequently, their ability to reach a larger aftermarket share (equations 9 and 10). As long as the OMs gain technological advantage, $c_s'(\overline{q}) - c_r'(\overline{q}) \geq 0$, their profits increase. When $c_s'(\overline{q}) - c_r'(\overline{q}) \leq 0$, the technological gap lessens and OMs see their aftermarket share reduced. Thereafter, the profit under regulation decreases until it reaches the initial firm's profit $\pi_i^*(q_k^*)$ at $\overline{q} = \overline{q}_k^{\max}$ (at point g (h)), where the second effect overtakes the first one. Above this threshold, regulation results in net costs for the OMs. Total variation following an effective regulation is represented by bcg (efcgh) and the shaded area beyond gh (h).

Proposition 2 *Environmental regulations can increase firms' benefits in both the non-cooperative and the collusive cases:*

$$\overline{\pi}_i(\overline{q}_k) - \pi_i^*(q_k^*) > 0 \Longleftrightarrow \overline{q} < \overline{q}_k^{\max}.$$

In particular, this remains true when the environmental regulation is effective:

$$\overline{\pi}_i(\overline{q}_k) - \pi_i^*(q_k^*) > 0 \Longleftrightarrow q_k^* \leq \overline{q} < \overline{q}_k^{\max}$$

This result coincides with the Porter Hypothesis, which says that profits may increase in the industry with the application of environmental regulations. The present model corroborates the argument of Ambec and Barla (2007) under which the Porter Hypothesis requires the presence of at least one market imperfection beside the environmental externality. The phenomenon is here the result of two market characteristics.

The first is the threat of the outsider on the primary market, which keeps the original price at the minimum production cost. Hence, OMs cannot pass on the information through prices that a product is remanufacturable. The competitive final good producers do not benefit from remanufacturability and see no incentive in raising production costs. Therefore, the selling price stays $p_m = c_m(0)$. When the regulation takes place, the selling price p_m carries the information up to the point justified by the public intervention ($p_m = c_m(\overline{q})$). This result shows how free-entry on the original alternator market has prevented OMs from engaging in remanufacturing initiatives and how the asbestos ban was welcomed by the industry.

The second characteristic occurs in the non-cooperative scenario. From *Proposition 1*, it is known that collusion leads to higher profits. Here, the regulation solves for this collective action problem. Although non-cooperation is not a necessary condition in confirming the Porter Hypothesis, it increases the extent to which regulations generate profits. This specific effect is graphically represented in Figure 3 by the area framed above and below by the horizontal lines $\pi_i^*(q_c^*)$ and $\pi_i^*(q_{nc}^*)$, and to the left by eb. André *et al.* (2009) obtains similar results when a duopoly simultaneously choose between the production of a "standard" or a "green" product. A discrete choice of options can keep the standard quality as the Nash equilibrium, even if Pareto dominated by the green choice. Therefore, a regulation that forces cooperation between firms for the environmentally-friendly option can benefit firms, consumers and the environment. This additional role given to the regulation explains the difference between the non-cooperative and the collusive scenarios and leads to propositions 3 and 4.

In view of the positive variation in profits, any regulation below $\overline{q}_k^{\max}$ should be positively supported by the OMs. In contrast, regulations above $\overline{q}_k^{\max}$ are likely to meet resistance in their application. The difference in profits before and after the regulation (equation 17) can therefore be interpreted as the *intensity* of compliance or resistance towards the regulation. Hence:

Proposition 3 *It is always easier to introduce an environmental regulation $\overline{q}$ under the non-cooperative case:*

$$\overline{\pi}_i(\overline{q}_{nc}) - \pi_i^*(q_{nc}^*) > \overline{\pi}_i(\overline{q}_c) - \pi_i^*(q_c^*)$$

Proposition 4 *The maximum level of regulation positively supported by the industry is larger under the non-cooperative case:*

$$\overline{q}_c^{\max} < \overline{q}_{nc}^{\max}.$$

In the absence of environmental regulation, the government can promote collusion as a substitute for regulation. However, when a regulation is scheduled, collusion should be repressed since non-cooperation better supports the regulation.

4.2 Intervention maximizing OMs' profit

Let $\overline{q}^*$ denotes the optimal regulation that would be chosen by the OMs. This scenario differs from the collusive case in the absence of regulation; for whichever level of remanufacturability chosen by the OMs, the outsider, constrained by the regulation, will not have the opportunity to produce at lower costs and, consequently, the threat vanishes. With $p_{m1} = p_{m2} = c_m(\overline{q})$, the maximization problem is:

$$\max_{\overline{q}\geq 0} \overline{\pi}_i = \sum_{t=1}^{b} \beta_l^t [\delta r_i^*(\overline{q})^2]$$
$$\text{s.t. } r_i^*(\overline{q}) = \frac{\delta + c_s(\overline{q}) - c_r(\overline{q})}{3\delta}.$$

The optimal condition is:

$$\frac{\partial \overline{\pi}_i}{\partial q} = 0 \Longleftrightarrow c_s'(\overline{q}^*) - c_r'(\overline{q}^*) = 0 \tag{18}$$

and the second-order condition is always satisfied. Note that $\overline{q}^*$ coincides with $\widehat{q}$, the level of remanufacturability that maximizes the OMs' technological advantage (see equation 10). Figure 3 displays $\overline{q}^*$ and $\overline{\pi}_i(\overline{q}^*)$, the privately optimal regulation and the corresponding profit. Comparing the optimal conditions for the determination of $\overline{q}^*$, q_c^* and q_{nc}^* leads to the following propositions:

Proposition 5 *The regulation preferred by the private sector leads to a level of remanufac-*

turability above the one chosen in absence of regulation:

$$\overline{q}^* > q_c^* > q_{nc}^*$$

Proof: From *Proposition 1*, it is already known that $q_c^* > q_{nc}^*$. The optimal conditions (11) and (13) for the choice of q in absence of environmental regulation imply a positive value of $(c_s'(q) - c_r'(q))$. Since $c_s''(q) - c_r''(q) < 0$ in this neighbourhood (equation 10), it is straightforward to see that the condition leading to the private optimal choice of regulation (18) results in $\overline{q}^* > q_c^* > q_{nc}^*$.

Proposition 6 *The size of remanufacturing activities (for the OMs) is maximized if and only if the public sector fixes the regulation at the level preferred by the OMs:*

$$\frac{\partial r_i^*}{\partial \overline{q}} = \frac{(c_s'(\overline{q}) - c_r'(\overline{q}))}{3\delta} = 0 \Longleftrightarrow \overline{q} = \overline{q}^*$$

When the regulation is selected by the private sector, OMs take into account the fact that the entire production cost is covered by the selling price. They can therefore seize the maximum aftermarket share by costlessly choosing the level of remanufacturability leading to their largest technological advantage. When $\overline{q} = \overline{q}^*$, OMs's profits are maximized as well as their aftermarket size.

When OMs' remanufacturing activities pollute significantly less than IRs', the social planner may want to maximize the OMs' aftermarket share to the detriment of higher remanufacturability by choosing $\overline{q} = \overline{q}^*$.

4.3 Welfare analysis

On the inelastic original market, consumer surplus varies only with the price. Hence, in equilibrium, it can be defined as $S_m = S_m(p_m) = S_m(c_m(\overline{q}))$ where $S_m(a) - S_m(b) = -[c_m(a) - c_m(b)]$ (or equivalently $S_m'(c_m(\overline{q})) = -c_m'(\overline{q})$). Using the consumer surplus on the remanufacturing market, $S_r(q)$ (equation 14), total consumer surplus in the presence of a regulation becomes:

$$S(\overline{q}_k) = S_m(\overline{q}) + \sum\nolimits_{t=1}^{b} \frac{\beta_l^t}{2} \left[(1-\delta) + \delta r_i^*(\overline{q}_k)^2 + 2(\alpha - c_s(\overline{q}_k))\right].$$

The change in consumer surplus following an environmental regulation is defined by:

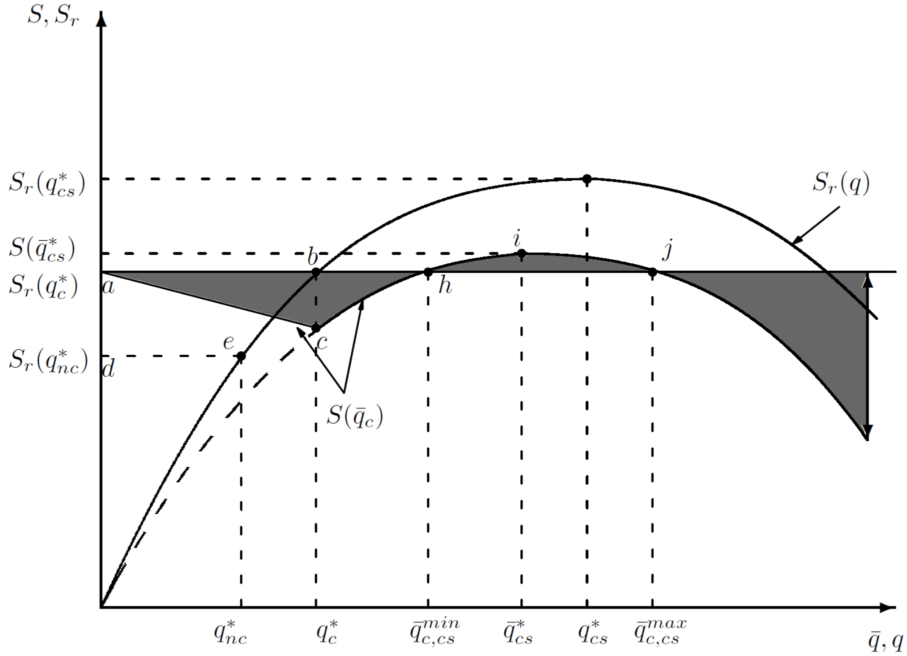
$$S(\overline{q}_k) - S_r(q_k^*) = \begin{cases} -(c_m(\overline{q}) - c_m(0)) \text{ if } q_k^* \geq \overline{q} \\ -(c_m(\overline{q}) - c_m(0)) + \\ \quad \sum\nolimits_{t=1}^{b} \frac{\beta_l^t}{2} \left[\delta(r_i^*(\overline{q})^2 - r_i^*(q_k^*)^2) - 2(c_s(\overline{q}) - c_s(q_k^*))\right] \text{ if } q_k^* \leq \overline{q} \end{cases} \tag{19}$$

Figure 4 a) illustrates a particular case of equation (19) in the collusive scenario. Figure 4 b) combines both the collusive and the non-cooperative cases. The upper curve is the consumer surplus with respect to the level of remanufacturability in the absence of regulation. The horizontal line $S_r(q_c^*)$ (respectively $S_r(q_{nc}^*)$) is the consumer surplus in the collusive (non-cooperative) case where, following *Proposition 1,* $S_r(q_c^*) > S_r(q_{nc}^*)$. In the presence of regulation, the lower curve shows the consumer surplus if the industry were to adopt exactly $\overline{q}$, however for low levels of regulation, the industry keeps producing at q_k^*. The vertical distance between the curves $S(\overline{q}_k)$ and $S_r(q_k^*)$ describes the difference in consumer surplus due to all possible level of regulation. The medium and dark (light and medium) shade areas exhibit the collusive (non-cooperative) case.

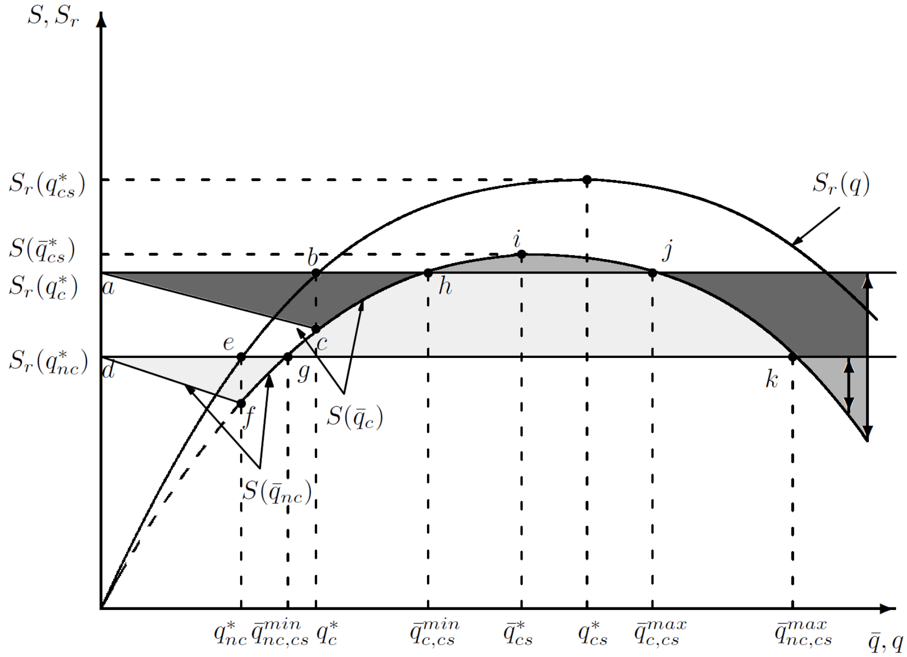
When the regulation is non-effective (*i.e.* for $q_k^* \geq \overline{q}$), the level of remanufacturability stays fixed but the price increases on the original market. Consumer surplus is therefore reduced by $-(c_m(\overline{q}) - c_m(0))$, illustrated in the triangle abc (def).

Proposition 7 *A non-effective environmental regulation lets the social welfare that equally weights total profits and consumer surplus unchanged.*

$$[S(\overline{q}_k) - S_r(q_k^*)] + 2[\overline{\pi}_i(\overline{q}_k) - \pi_i^*(q_k^*)] = 0 \ \textit{if} \ q_k^* \geq \overline{q}$$



a) the collusive case



b) the collusive and the non-cooperative cases

Figure 4: Consumer surplus with and without regulation

A non-effective regulation partially shifts the cost of remanufacturability from OMs towards final good producers and consumers. This can be seen using equations (17) and (19) expressing the change in profit and the change in consumer surplus. Considering the environmental neutrality of non-effective regulations, this money transfer leaves the social welfare unchanged.

When the regulation is effective, it can be shown that for some specific scenarios, a variation in the level of remanufacturability reduces prices of remanufactured products and increases the share of high quality goods on the aftermarket so that the net variation in consumer surplus is positive. Let $\overline{q}^*_{cs}$ be the effective environmental regulation that *locally* maximizes consumer surplus. The subscript cs designates consumer surplus. The constraints for a maximum are:

$$\begin{aligned} -c'_m(\overline{q}^*_{cs}) + \sum_{t=1}^{b} \beta_l^t \left[\frac{(c'_s(\overline{q}^*_{cs}) - c'_r(\overline{q}^*_{cs}))}{3} r_i^*(\overline{q}^*_{cs}) - c'_s(\overline{q}^*_{cs}) \right] &= 0. \\ -c''_m(\overline{q}^*_{cs}) + \sum_{t=1}^{b} \beta_l^t \left[\frac{(c''_s(\overline{q}^*_{cs}) - c''_r(\overline{q}^*_{cs}))}{3} r_i^*(\overline{q}^*_{cs}) + \frac{(c'_s(\overline{q}^*_{cs}) - c'_r(\overline{q}^*_{cs}))^2}{3\delta} - c''_s(\overline{q}^*_{cs}) \right] &\leq 0 \end{aligned}$$

Comparing with the optimality conditions for the choice of q^*_{nc} and q^*_c (equations 11 and 13), there exists (at least) one local maximum for the function (19) only if $\overline{q}^*_{cs} \geq q^*_k$, which occurs when the decreasing remanufacturing cost c'_s is large enough compared to the increasing original production cost c'_m, when evaluated at q^*_k.[21] Otherwise, consumer surplus strictly decreases with more stringent regulation. The regulation can be welfare improving for the consumer only if $S(\overline{q}^*_{cs}) \geq S(q^*_k)$, in which case the net positive variation in consumer surplus is illustrated by the area hij (ghijk) for the collusive (non-cooperative) case. When the regulation becomes too stringent, the market share of high quality remanufactured products drops, which causes the consumer surplus to decrease. At $\overline{q}^{\max}_{k,cs}$ (beyond j (k)), the regulation

[21]Note that, under certain conditions, the consumer surplus function in the presence of regulation allows for multiple maxima for $\overline{q} \geq q^*_k$. For simplicity, the following results are presented for cases where there is at most one maximum.

is a net cost for the consumer. This leads to the following propositions:

Proposition 8 *When $S(\overline{q}^*_{cs}) \geq S(q^*_k)$, an effective environmental regulation can increase consumer surplus:*

$$S(\overline{q}) - S_r(q^*_k) \geq 0 \text{ if } \overline{q}^{\min}_{k,cs} \leq \overline{q} \leq \overline{q}^{\max}_{k,cs}$$

More particularly, when $S(\overline{q}^*_{cs}) \geq S(q^*_k)$ and $\overline{q}^{\min}_{k,cs} \leq \overline{q}^{\max}_k$, an effective environmental regulation can increase both profits and consumer surplus:

$$\overline{\pi}_i(\overline{q}_k) - \pi^*_i(q^*_k) \geq 0 \text{ and } S(\overline{q}) - S_r(q^*_k) \geq 0 \text{ if } \overline{q}^{\min}_{k,cs} \leq \overline{q} \leq \min\{\overline{q}^{\max}_{k,cs}, \overline{q}^{\max}_k\}$$

Under some circumstances, the government can apply an environmental regulation for which, in addition to environmental advantages, producers and consumers benefit from higher profits and lower prices.

Proposition 9 *It is always easier to introduce an effective environmental regulation under the non-cooperative case:*

$$S(\overline{q}_{nc}) - S_r(q^*_{nc}) < S(\overline{q}_c) - S_r(q^*_c)$$

Proposition 10 *When $S(\overline{q}^*_{cs}) \geq S(q^*_k)$ for $k = c, nc$, the range of regulations positively supported by consumers is larger under the non-cooperative case:*

$$\overline{q}^{\max}_{nc,cs} - \overline{q}^{\min}_{nc,cs} > \overline{q}^{\max}_{c,cs} - \overline{q}^{\min}_{c,cs}.$$

This stays true when $S(\overline{q}^*_{cs}) \geq S(q^*_{nc})$ and $S(\overline{q}^*_{cs}) \leq S(q^*_c)$ since

$$\overline{q}^{\max}_{nc,cs} - \overline{q}^{\min}_{nc,cs} \geq 0$$

Propositions 9 and *10* say that, when the difference in consumer surplus before and after the regulation is interpreted as the intensity of political support for the regulation, the government should repress collusion. These results are in line with *Propositions 3* and *4* where firms are more likely to comply with the public intervention when they compete on the level of remanufacturability.

5 Conclusion

Original manufacturers produce a component as an input for the final good where the threat of an outsider keeps the input's price at the minimum production cost. At the same time, they select the technology determining the level of remanufacturability of their products. Later, consumers of the final good have to replace the specific component. They consider products remanufactured by either independent remanufacturers or original manufacturers, and they are willing to pay a price premium for the latter. In this set-up, used products can be remanufactured by any firms, causing original manufacturers to suffer from free-riding on their technology selection and discouraging investment in remanufacturing-oriented designs. When the original manufacturers collude on the level of remanufacturability, they only face the externality of independent remanufacturers and select a higher level of remanufacturability. Collusion benefits producers and, by reducing prices on the aftermarket, consumers.

Remanufacturing benefits the population through less post-consumption waste, lower energy and raw material consumptions, and lower prices for replacement products. It can also benefit the industry through the generation of positive profits. While the gains of remanufacturing are shared among the society, the costs of remanufacturing-oriented technology are born solely by the original manufacturers. Consequently, public regulation may be necessary.

The introduction of an environmental regulation, which imposes a minimal level of remanufacturability, justifies a price increase on the primary market. As a consequence, the cost of complying with the regulation is redirected towards final good producers and consumers. Hence, original manufacturers can see their profits increase. This observation corroborates the Porter Hypothesis. Under some circumstances, the environmental regulation can also increase consumer surplus.

A social planner who wants to stimulate remanufacturing activities can consider allowing private collusion as an alternative to environmental regulation since it leads to a higher level of remanufacturability. Moreover, collusion leads to a larger supply of high quality remanufactured products and to lower prices on the aftermarket and, hence, increases consumer surplus. The application of an environmental regulation reduces the threat of the outsider and solves for the collective action problem. If the social planner opts for this option, it should repress private collusions. When the variation in profits following the public intervention is interpreted as the industrial degree of cooperation with the regulation, original manufacturers will always offer stronger support, or lower opposition, when the technology choice is initially subject to free-riding.

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